

# Single production of doubly charged Higgs bosons at hadron colliders

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We reconsider the single production of the doubly charged Higgs bosons  $\Delta_R^{++}$  and  $\Delta_L^{++}$  at the LHC and TEVATRON in the framework of the left-right symmetric model and the Higgs triplet model. We show that in the left-right symmetric model the production of  $\Delta_R^{++}$  by Drell-Yan process via  $W_R$  exchange may give the dominant contribution. The same channel for the production of  $\Delta_L^{++}$  in the Higgs triplet model is insignificant.

Due to the recent convincing experimental evidences, in particular those on atmospheric and solar neutrinos [1,2], the existence of neutrino masses below the scale  $O(1\text{ eV})$  has now become more and more established. Many theoretical explanations for the lightness of neutrinos has been suggested and discussed in the literature [3]. Perhaps the most attractive and natural one among them is the see-saw mechanism [4]. In this mechanism one introduces, in addition to the ordinary Dirac mass term, Majorana mass terms for the left-handed and right-handed neutrinos. Neutrinos form a special category among basic fermions in that they can have, due to their electric and color neutrality, such lepton number violating mass terms.

The Majorana mass terms result from the Yukawa couplings of lepton doublets with triplet Higgs fields. The left-handed Higgs triplet,  $\Delta_L = (\Delta_L^0, \Delta_L^+, \Delta_L^{++})$ , that gives rise to the Majorana mass of the left-handed neutrinos, was first

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introduced by Gelmini and Roncadelli [5], while the right-handed Higgs triplet  $\Delta_R = (\Delta_R^0, \Delta_R^+, \Delta_R^{++})$  naturally appears in the so-called left-right symmetric model [6], where it also takes care of the breaking of the left-right symmetry.

The origin of neutrino masses is quite difficult to figure out just by looking at the low-energy phenomenology of neutrinos. The phenomena like neutrino oscillations, leptonic decays of particles and the neutrinoless double beta decay are quite independent of the mechanism by which neutrino masses are created. Indirect information could, however, be obtained by studying the physics related to the mass generation mechanism in high-energy collision process. Particularly, indirect information on the see-saw mechanism can be obtained through the phenomenology of the triplet Higgs fields.

The phenomenology of Higgs triplets differs quite much from that of the Standard Model (SM) Higgs doublets. The most dramatic difference certainly is the existence of a doubly charged scalar field ( $\Delta^{++}$ ) within the triplets. In addition, low-background signals are easy to find due to fact that the Yukawa couplings of the triplet Higgs bosons violate lepton number conservation, a symmetry strictly obeyed by the Standard Model interactions.

By studying the high-energy phenomenology of the triplet Higgs fields one could get information on the properties of these fields and on the strengths of their Yukawa couplings [7], [8], [9]. Several constraints on Yukawa couplings can be obtained from experimental data [10], the most stringent limit [12] coming from the recent results on muonium-antimuonium conversion [11]:

$$\frac{\sqrt{h_{ee} \cdot h_{\mu\mu}}}{M_{\Delta^{++}}} < 0.44 \text{ TeV}^{-1} . \quad (1)$$

The tightening of these limits makes the study of the high-energy phenomenology of the triplet Higgs bosons at future hadronic colliders interesting and well motivated.

Most of the previous studies of the production of the doubly charged Higgs bosons at hadronic colliders have concentrated to two production mechanisms: single production via  $WW$ -fusion and the  $\Delta^{++}\Delta^{--}$  pair production via s-channel photon and Z-boson exchange. A comparison of these two production mechanisms at the LHC environment was presented in [13]. A more general analysis of various production mechanisms of the doubly charged Higgs bosons

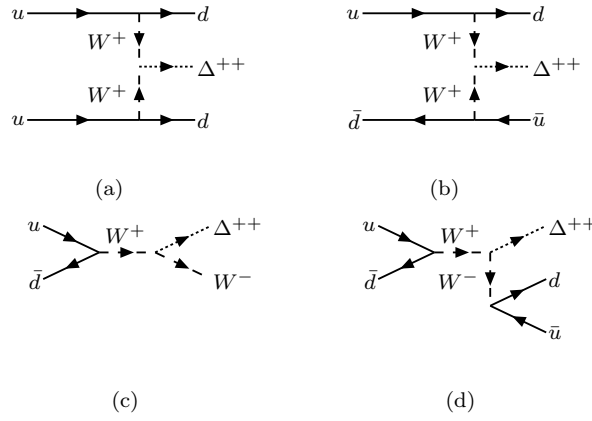


Fig. 1. The Feynman diagrams for the single  $\Delta^{++}$  production via the  $WW$  fusion ((a) and (b)), and via the Drell-Yan process ((c) and (d)).

at future colliders was done in [14]. This analysis was, however, restricted to the case of the left-handed Higgs triplet  $\Delta_L^{++}$ , where one can safely neglect the  $WW\Delta$  vertex. This vertex is proportional to the VEV of the neutral member of the Higgs triplet, which in the case of the left-handed triplet is very small due to the constraint set by the  $\rho$  parameter. It was shown that the LHC could probe the left-handed doubly charged Higgs boson up to a limit of 950 GeV for  $M_{\Delta^{++}}$ . The LHC discovery potential in the case of the process  $pp \rightarrow e^- e^- \mu^- \mu^-$  was estimated in [15] to be  $M_{\Delta_L^{++}} < 850$  GeV. It should be noted that both of these numerical results were obtained with the assumption that  $\Delta_L^{++}$  decays to leptons only.

In this paper we shall consider some new aspects, not addressed in the previous studies, of the production of the doubly charged Higgs bosons at hadron colliders LHC and TEVATRON. In particular, we will investigate the single  $\Delta^{++}$  production via the reaction  $pp \rightarrow \Delta^{++} q q$  (see Fig. 1 a and b). This  $WW$  fusion process is experimentally interesting due to its clear dilepton signature from the decay of the doubly charged Higgs boson. We also study the Drell-Yan-type production of a single  $\Delta^{++}$  via the process  $pp \rightarrow \Delta W \rightarrow \Delta^{++} q q$  (see Fig. 1 c and d). As we will see below, this process can be the dominant production mechanism for a wide range of parameter values in the case of the  $\Delta_R^{++}$ . Both of the processes go through the  $WW\Delta$  vertex. The production threshold in the single production processes is lower than that in the pair production, and therefore these processes are particularly interesting phenomenologically as they probe a larger mass range of  $\Delta^{++}$ .

We have studied the  $WW$  fusion and Drell-Yan processes in two models, in

the left-right symmetric model (LRM) and in the Higgs Triplet model (HTM) where an additional Higgs triplet is added to the SM. A detailed description of the LRM is found in [6], whereas the HTM is discussed in [16].

We have evaluated the production cross sections by using the CompHEP package [17]. The Feynman rules for the HTM were checked with the help of the LanHEP package [18]. As usual, we have calculated cross sections with two initial quarks and appropriately convoluted them with the quark structure functions:

$$\sigma_{p,(anti)p \rightarrow final\ state} = \sum_{i,j} \int dx_1 dx_2 f_i(x_1) \cdot f_j(x_2) \cdot \hat{\sigma}_{ij}(x_1 P_1, x_2 P_2) \quad (2)$$

where  $i, j$  enumerate quarks inside protons (antiprotons),  $x_{1,2}$  denote the fraction of incident momenta  $P_{1,2}$  carried by the quarks and  $\hat{\sigma}$  denotes the appropriate quark cross section. For our calculations we have used the MRS structure functions implemented by the CompHEP. For the final state quark jets we have applied an angular cut of  $|\cos(\theta)| < 0.9$  and an energy cut of  $E > 10$  GeV.

The production cross sections of the right-handed and left-handed Higgs triplet boson at LHC energy ( $\sqrt{s} = 14$  TeV) are presented in Fig. 2. We show separately cross sections arising from the  $WW$  fusion and from the Drell-Yan process. For the case of the LRM (see Fig. 2a) one finds that at relatively small values of the mass of the doubly charged Higgs boson the Drell-Yan process via  $W_R$  yields the dominant contribution. The cross section depends on the  $W_R$  mass, and the greater this mass is, the more heavy  $\Delta^{++}$  can be probed, assuming that the Drell-Yan process is the dominant production mechanism, as it is for the most probable values of the masses of  $W_R$  and  $\Delta_R^{++}$ .

However, for the left-handed triplet Higgs boson (see Fig. 2b) situation is completely different. Here the  $W_L W_L$ -fusion is the main production channel for all reasonable values of the doubly charged Higgs boson mass. The explanation of this fact is the essential difference between  $W_L$  and  $W_R$  masses ( $M_{W_L} = 80$  GeV,  $M_{W_R} > 700$  GeV [19]).

In Figure 3 we show the cross sections of the single  $\Delta^{++}$  production at the Tevatron. One can conclude that for the anticipated annual luminosity of the Tevatron,  $\sim 15\text{fb}^{-1}$ , [20] the left-handed doubly charged Higgs bosons are unobservable. On the other hand, several the right-handed triplet boson  $\Delta_R^{++}$

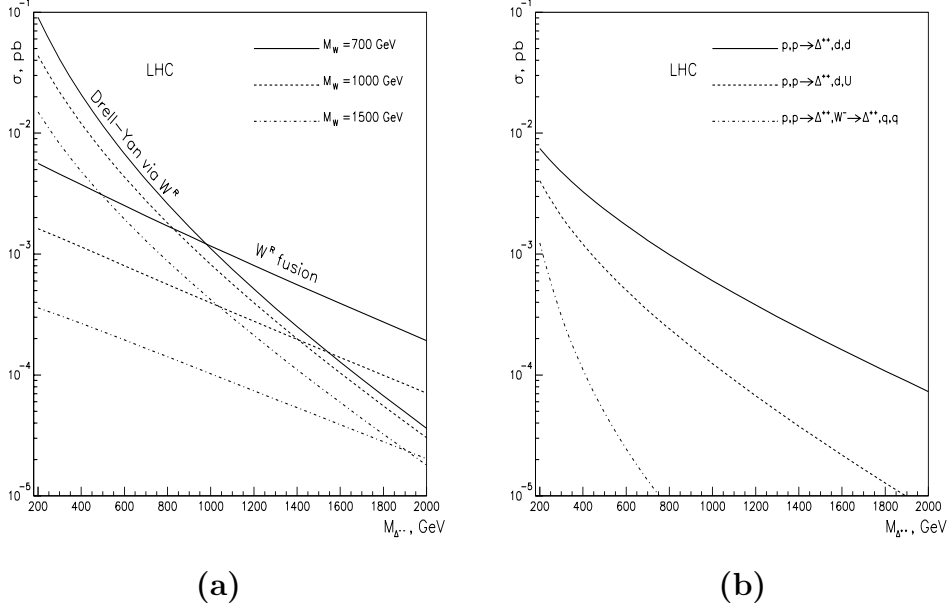


Fig. 2. The production cross sections of  $\Delta_R^{++}$  (a) and  $\Delta_L^{++}$  (b) at the LHC as a function of the mass  $M_{\Delta^{++}}$ . In (a) the solid line corresponds to  $M_{W_R} = 700$  GeV, the dashed line to  $M_{W_R} = 1000$  GeV, the dash-dotted line to  $M_{W_R} = 1500$  GeV. In (b) the solid line corresponds to  $W_L$  fusion with two  $d$ -jets in the final state ( $pp \rightarrow \Delta^{++} dd$ ), the dashed line corresponds  $W_L$  fusion with  $d$ - and  $\bar{u}$ -jets in the final state ( $pp \rightarrow \Delta^{++} d\bar{u}$ ), the dash-dotted line corresponds to the Drell-Yan process with s-channel  $W_L$  exchange ( $pp \rightarrow \Delta^{++} W_L \rightarrow \Delta^{++} qq$ ).

events were possible to detect if  $M_{W_R}$  is near 100 GeV, the  $W_R W_R$ -fusion giving the dominant contribution.

The best signature for the observation of the doubly charged Higgs bosons comes from the decay mode  $\Delta^{++} \rightarrow l^+ l^+$ . This mode may be dominant, depending on the mass splittings between scalars within the triplets and the vacuum expectation value of Higgs triplet [7]. The same-sign two-lepton background from the SM processes is always associated with at least two neutrinos due to lepton number conservation, while the signal process has very little missing energy.

In order to distinguish the Drell-Yan and fusion processes in the case of the LRM, we have studied the dependence of the cross section on the opening angle between the two outgoing like-sign leptons. For the fusion channel the cross section occurs to be more forward peaked than for the Drell-Yan process. However, it turns out that the shape of the distribution strongly depends

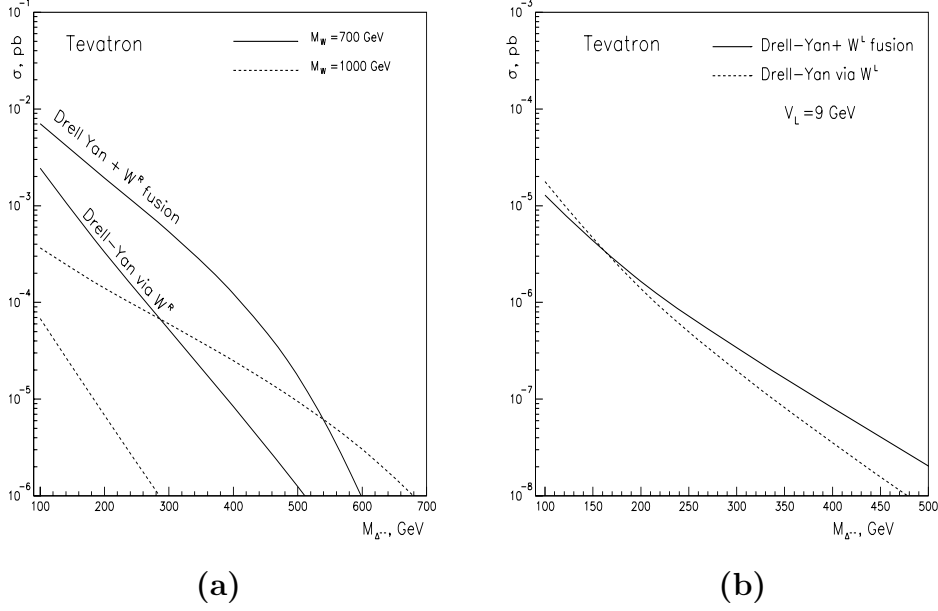


Fig. 3. The production cross sections of  $\Delta_R^{++}$  (a) and  $\Delta_L^{++}$  (b) at the TEVATRON as a function of the mass  $M_{\Delta^{++}}$ . In (a) the solid line corresponds to  $M_{W_R} = 700$  GeV, the dashed line c to  $M_{W_R} = 1000$  GeV. In (b) the solid line corresponds to the process of  $W_L$  fusion with  $d$ - and  $\bar{u}$ -jets in the final state ( $p\bar{p} \rightarrow \Delta^{++} d\bar{u}$ ), dashed line corresponds to the Drell-Yan process with s-channel  $W_L$  exchange ( $p\bar{p} \rightarrow \Delta^{++} W_L \rightarrow \Delta^{++} q\bar{q}$ ).

on the mass of the doubly charged Higgs boson and makes it practically impossible to distinguish between the two channels.

Nevertheless, these two channels can be separated due to completely different invariant mass distributions of the final state quarks. One can see from Fig. 1, that in the Drell-Yan case the corresponding outgoing quarks are mostly produced by decays of real  $W_R$ 's and hence their invariant mass distribution should have peak at  $M^{qq} = M_{W_R}$ . It is not true for the fusion channel; the corresponding distribution should not have this kind of peak. In Figure 4 we show the  $M^{qq}$  distributions for the both channels. The doubly charged Higgs boson mass is chosen to be 800 GeV, while  $M_{W_R}$  mass is set to 700 GeV (a), 1000 GeV (b) and 1500 GeV (c). Of course, the actual data will contain both channels, and we show this actual  $M^{qq}$  distribution by solid curve in each of three cases of Figure 4, the distribution for the Drell-Yan channel is shown by a dashed line, for the fusion channel by a dashed-dotted line. As a matter of fact, the actual  $M^{qq}$  distribution is to a good extent just a sum of Drell-

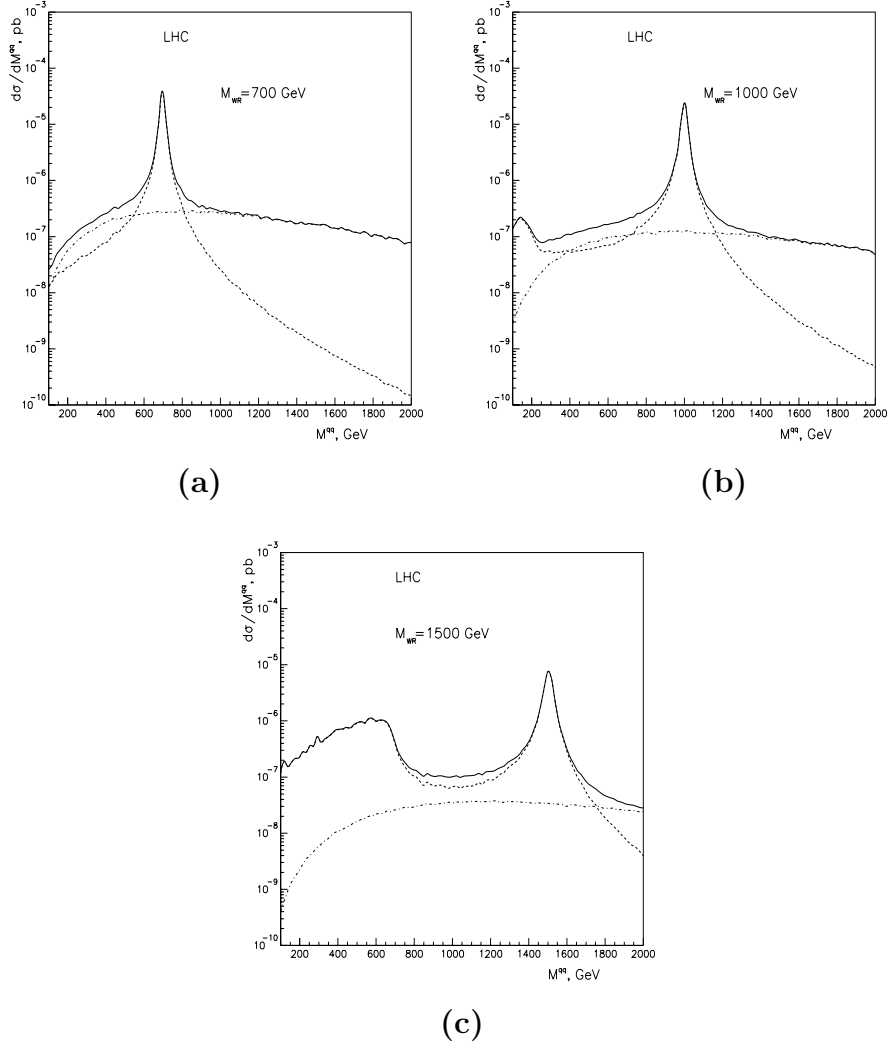


Fig. 4. The invariant mass distribution of the final quarks at the LHC for different values of  $M_{W_R}$ . The mass  $M_{\Delta^{++}} = 800$  GeV. The solid line corresponds to the total cross section, the dashed line to the Drell-Yan contribution, the dashed-dotted line to the contribution of fusion. (The small structures of the curves are due to numerics).

Yan and fusion distributions, since for the case of fusion quark-antiquark final states are suppressed and may be safely neglected in comparison with quark-quark final states, while the latter are totally absent in the Drell-Yan channel. According to this, if one throws away the suppressed fusion final states, there cannot be any interference between the two channels.

One can notice an important threshold behaviour in the  $M^{qq}$  distribution

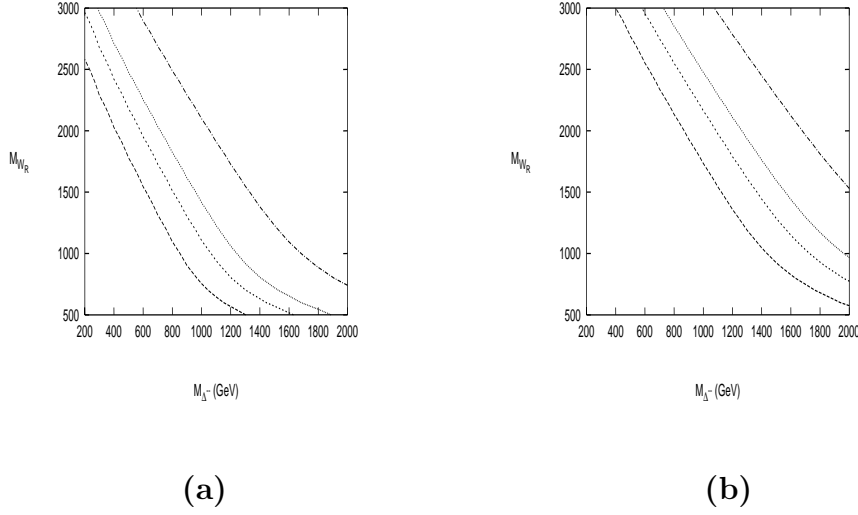


Fig. 5. The LHC discovery limits of  $\Delta_R^{++}$  in the LRM in the  $(M_{W_R} M_{\Delta^{++}})$ - plane at 1, 3, 5 and 10 events levels. The case (a) corresponds to dominantly bosonic decays, case (b) corresponds to leptonic decay channels only.

of the Drell-Yan channel (at  $M^{qq} = 200$  GeV in Fig 4b and at  $M^{qq} = 700$  GeV in Fig 4c): when  $M^{qq} + M_{\Delta^{--}} \geq M_{W_R}$ , the differential cross section turns down. This happens due to an s-channel  $W_R$  propagator suppression: due to structure functions the value of  $s$  of the incoming quarks is not fixed and it may include the  $W_R$ -propagator resonance. However, as soon as  $M^{qq}$  exceeds the abovementioned limit, the  $W_R$  propagator goes off-shell. We used  $\Gamma_{W_R} = \Gamma_{W_L} \cdot M_{W_R}/M_{W_L}$  for the  $W_R$  width. The main contribution to cross sections of Fig. 4 comes from real  $W_R$ 's of the Drell-Yan channel, with a subsequent decay of  $W_R$  to quark-antiquark pairs.

In Figure 5 we present the discovery limits of the single production of  $\Delta^{++}$  at LHC in the LRM. The contours are drawn in the  $(M_{W_R} M_{\Delta^{++}})$ - plane, and they correspond to the 1, 3, 5 and 10 events for the luminosity of  $100 fb^{-1}$ , with the 0.9 detection efficiency of the each final state muon (lepton). We have considered two light-quark jets in the final state (i.e.  $u, d, s, c$  and corresponding antiquarks), and the branching ratio of  $W_R$  decay into light quark-antiquark pair was estimated to be 0.65, i. e. we have neglected the bosonic decay modes for  $W_R$ . The number of observed events in this case



Table 1

The 95% probability mass discovery limits (given in GeV) of doubly charged Higgs bosons in LRM. Results are shown for  $Br(\Delta^{++} \rightarrow \mu^+ \mu^+) = 0.06, 0.1, 0.15, 0.2, 0.25, 0.3, 0.33$ . Columns correspond to the  $M_{W_R} = 1000, 1500, 2000$  GeV. In all cases we assume an integrated luminosity of  $L = 100 \text{ fb}^{-1}$ .

$Br.ratio$	$M_{W_R} = 1000$	$M_{W_R}=1500$	$M_{W_R}=2000$
$(\Delta^{++} \rightarrow \mu^+ \mu^+)$	$M_{\Delta^{++}}$	$M_{\Delta^{++}}$	$M_{\Delta^{++}}$
0.06	1250	960	700
0.1	1400	1100	870
0.15	1600	1250	990
0.2	1730	1360	1080
0.25	1820	1450	1170
0.3	1900	1520	1200
0.33	1970	1560	1250

strongly depends on the branching ratio of  $\Delta^{++} \rightarrow \mu^+ \mu^+$ . For  $M_{\Delta^{++}} > 2M_{W_R}$  the decay channel  $\Delta^{++} \rightarrow W_R W_R$  is opened. However, even before that other bosonic decay channels, e.g.  $\Delta^{++} \rightarrow \Delta^+ W_R^+$  and  $\Delta^{++} \rightarrow \Delta^+ \Delta^0$ , may become possible. Their decay widths strongly depend upon the at present unknown mass spectrum of the triplet scalars and Higgs self-couplings. In order to take this ignorance into account we take the branching ratio

$$Br_{\mu^+ \mu^+} \equiv \Gamma(\Delta^{++} \rightarrow \mu^+ \mu^+)/\Gamma(\Delta^{++} \rightarrow all) \quad (3)$$

as a phenomenological parameter in our estimates. We assume the maximal natural value of this branching ratio to be  $1/3$ , which corresponds to the case where the doubly charged Higgs boson decays always to leptons with the equal flavour diagonal Yukawa couplings for all three families. The plots in Fig. 5 a correspond to the  $Br_{\mu^+ \mu^+} = 0.06$ , and the plots in Fig. 4 b - as the most optimistic case - corresponds to  $Br_{\mu^+ \mu^+} = 1/3$ .

In Table 1 we present the 95% C.L. discovery limits of the  $M_{\Delta^{++}}$  for the LHC in the LRM. We choose values of the  $W_R$  boson mass to be 1000, 1500, or 2000 GeV and calculate the discovery limits for the different values of the branching ratio  $Br_{\mu^+ \mu^+}$ . As can be seen from the Table, even for a relatively heavy right-handed W-boson the discovery limit for  $\Delta^{++}$  remains quite high.

In conclusion, the single production of the doubly charged Higgs bosons via the

processes of Fig. 1 offers a way to improve significantly the discovery limits of  $\Delta_R^{++}$  for a wide range of  $W_R$  masses. They also probe the  $WW\Delta$  vertex which is inevitable for the triplet Higgs interactions. However, we showed that for the TEVATRON energies it is impossible to detect the effects of these vertices, while at the LHC energies they really dominate the  $\Delta_R^{++}$  production. The analysis of final quarks  $M_{qq}$  distribution may reveal the effects of Drell-Yan channel contribution due to characteristic peak behavior at  $M^{qq} = M_{W_R}$ . The discovery of this peak would be an indication of the existence doubly charged Higgs boson  $\Delta_R^{++}$ .

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